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FLAME PROPAGATION INTO THE GAP OF SOLID PROPELLANT GRAIN (I)

by

T. Godai

National Aerospace Laboratory, Tokyo, Japan, Report No. 91, pp. 1-12 (1965)

Translated from the Japanese

July 1967

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The flame propagation into a narrow gap, which is prepared perpendicular to the prime burning surface of solid propellant grain, has been experimentally investigated using the test specimens of polyester-ammonium perchlorate composite propellants.

Experimental results show that the flame propagates from the original burning surface into a gap when its width is larger than some critical value, and vice versa. This means that there always exists the critical value for the width of gap which is the threshold of propagation and nonpropagation of flame into it. The critical value is primarily the function of linear burning rate and the overall mechanism of flame propagation into a gap of solid propellant grain will be explained with the quenching theorem.

It is expected that further work will give a useful measure to the setting of standards of nondestructive testing of solid propellant grains and motors.

1. INTRODUCTION

Solid state rocket motors have solid propellants charged within the combustion chamber, which is a pressure vessel, burn them and create thrust by exhausting the combustion gases through a nozzle affixed to one end of the combustion chamber. Combustion takes place at the exposed surfaces of the solid state propellant and in order to obtain a fixed combustion chamber pressure, the nozzle throat area and the burning area of the propellant are previously established. However, because of errors in the manufacture of the propellant or methods of handling, or poor design of propellant shape, or poor mechanical properties of the propellant, there are times when cracks occur in the propellant itself or separation takes place in the adhering surface between the propellant and the restrictor which is affixed to the propellant to prevent combustion. When this happens, since the combustion area becomes larger than the designed area, the combustion pressure in the combustion chamber increases beyond what is expected; the permissible pressure in the combustion chamber is sometimes exceeded and causes destruction of the combustion chamber. Accordingly, in order to prevent such accidents, it is necessary to detect beforehand cracks in the propellant or peeling of the restrictor. Currently, as nondestructive examination measures for solid rocket motors, X-rays and gamma rays are in general use. These methods are capable of detecting internal defects around 0.2 percent the size of the test specimen, for example, holes or bubbles 1 mm in diameter in solid propellants 500 mm thick. However, it is far more difficult to detect cracks or peeling between propellant and restrictor than it is to detect holes or bubbles.

Moreover, the increase in combustion area due to cracks and peeling between the propellant and restrictor is normally far greater than that caused by holes and bubbles. While it had been believed that cracks within the propellant and peeling of the restrictor were related to abnormal rise in combustion chamber pressure of solid rocket motors, there have been no actual examples of research conducted on this matter. It has not even been studied as to what width of cracks should be detected through nondestructive examination. If cracks are sufficiently wide, combustion will obviously take place on the inside surface of the cracks, but it is not clear whether combustion will take place on the inside surface of the cracks even if their widths were sufficiently narrow.

In this report we used polyester composite propellants to experimentally study ignition in the inside of cracks in solid propellants, that is to say, flame propagation into the inside of cracks.

2. EXPERIMENTAL PROCEDURES

The shape of propellant specimens used in this experiment is shown in Figure 1. Two sticks of propellant, each 25 mm long, having a square cross section 5 mm per side, were assembled with a tiny space between them to obtain a gap equivalent to a crack. After precision machining of the composite propellant, consisting of polyester resin fuel binder and ammonium perchlorate oxidizer, it is held between a bakelite panel and vinyl chloride panel and held in place with an adhesive to maintain the crack spacing. The gap was measured using a thickness gauge. By using a hard polyester composite propellant, it is possible to manufacture test specimens with accurate crack gaps. By using front and rear panels it is possible to ignore the external effects from the edges, and as the width of the crack is sufficiently wide in comparison to the crack spacing, we could consider this test specimen as being a two-dimensional model.

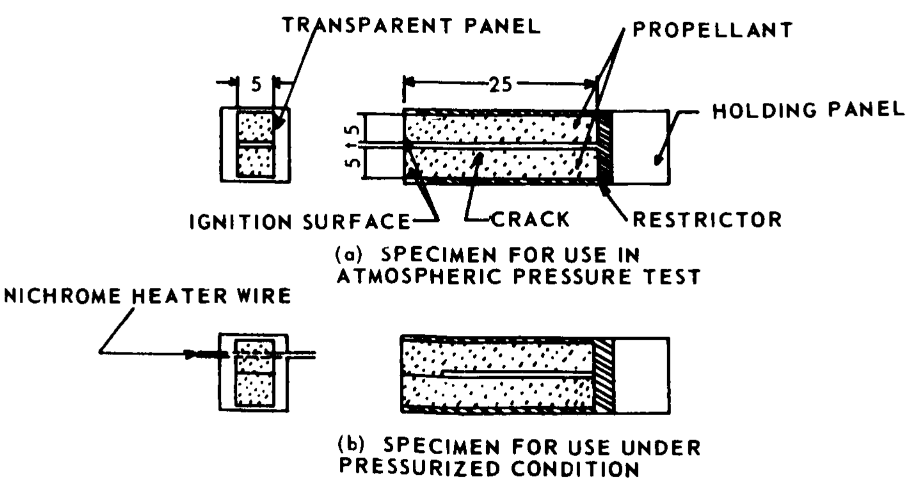

Figure 1. Details of Propellant Test Specimen

In general, ignition was undertaken by placing a heater wire against the surface of the propellant to be ignited. However, in experiments carried out under pressurized conditions, as shown in Figure 1(b), buried nichrome wires were used to ignite the propellant.

Using propellants with the same composition, test specimens were made differing only in the gapping of the cracks, and under the same conditions 10 to 40 specimens were ignited and burned. When the burning surface moves only perpendicularly to the crack and the inside of the crack does not ignite so that it burns just as if there were no cracks, we refer to this as "nonpropagation of flame into cracks." In contrast, when the flame does not merely move parallel with the initial ignition plane but also ignites and burns inside the cracks, we will refer to it as "propagation of flame into cracks." When flames propagate into the cracks, it is possible to oberve this via the transparent panel, and moreover it is accompanied by a fierce burning sound so that it is generally easy to determine propagation or nonpropagation. Representative examples of nonpropagation of flame into cracks and propagation into cracks are shown in Figure 2 (a) and (b), respectively.

As conditions of the experiments, the various parameters shown below were varied in order to obtain the threshold crack gap t^* for the propagation or nonpropagation of flame into the cracks. In tests conducted under normal atmospheric pressure, the test specimens were held vertically and ignited on the upper surface, but in tests undertaken under pressure the specimens were placed horizontally. Bases on results of preliminary tests, the position of the specimens had no effect on t^*. The parameters for the tests are as follows:

1) Initial temperature of the propellant.

2) Environmental pressure on the propellant.

3) Composition of the propellant.

Throughout the tests, the initial temperature of the propellant was at ambient temperature (approximately 20°C), and only in tests to determine the effects of initial temperature were the test specimens placed in a precision oven to give them temperatures of +25°C, O°C and -25°C.

The environmental pressure on the propellant is the pressure of the pressurizing air when test specimens were placed in a pressure chamber, equipped with a viewing port, and ignited and burned, and it was adjusted within the range between zero to 3.5kg/cm^2 G. As the volume of this pressure chamber is small, there is a danger that the pressure will rise beyond the initially established pressure when the test specimens starts to burn. Therefore, in order

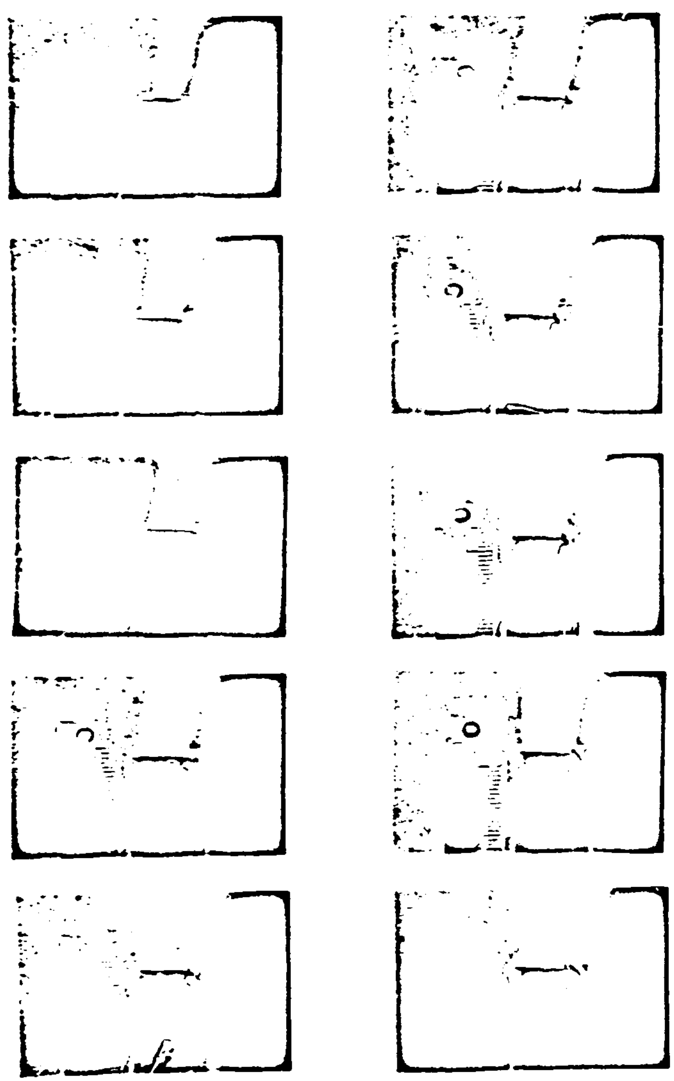

Figure 2(a). Combustion State when Flame does not Propagate into Cracks. Number of Frames Photographed - Approximately 1.5 Frames per Second

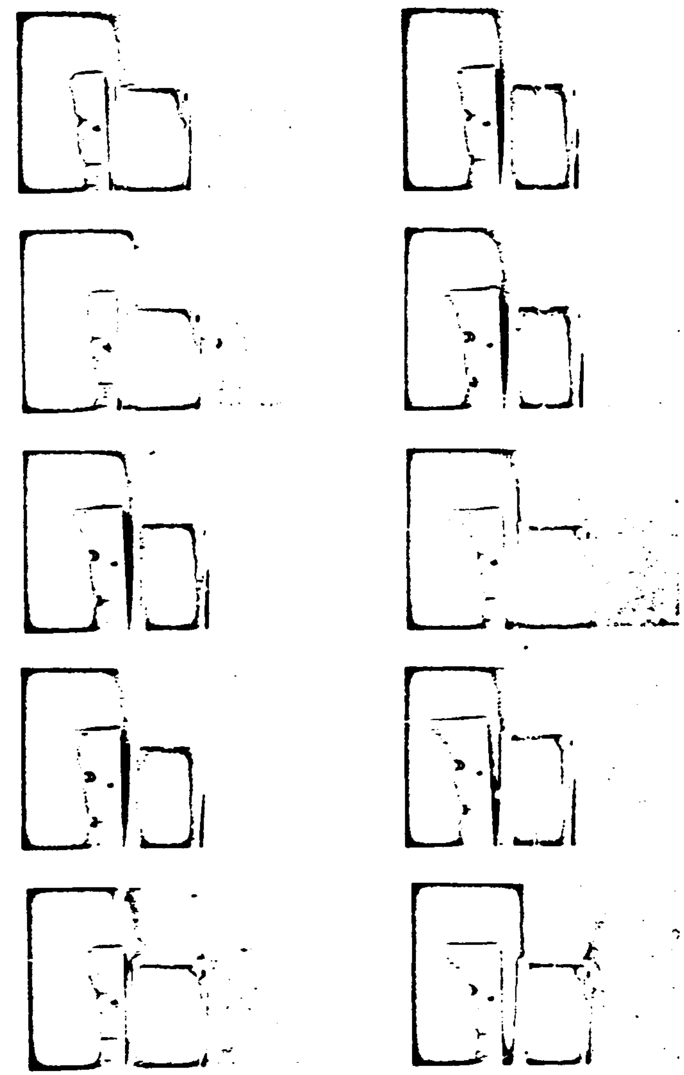

Figure 2(b). Combustion State when Flame Propagates into Cracks. Number of Frames Photographed - Approximately 3 Frames per Second to accurately obtain the pressure immediately before the flame propagated into the crack, the test specimens were shaped as shown in Figure 1(b). The pressure when flame propagates into the crack rises in three steps: air pressure prior to ignition, combustion pressure while burning on the surface without the crack, and combustion pressure after ignition of the inside of the crack. The pressure at the second stage was measured as being the environmental pressure of the propellant. If the flame does not propagate into the crack, the third stage pressure does not appear. Also, when tests were carried out in the pressure chamber, air was made to flow in parallel with the propellant test specimen in order to avoid dirtying of the observation port by combustion gases. Based on results of preliminary tests, no effect of this air flow was noted on t^*. One view of the pressure chamber is given in Figure 4.

The composition of the propellant used for measuring the effects of temperature and pressure was 75 percent ammonium perchlorate (AP) with average grain diameter of 80 to 100 microns. The composition of the propellants used for measuring the effects of propellant composition is given in Table I. The graininess of ammonium perchlorate given in Table I was measured using a microscope. The distribution of its graininess is shown in Figures 5(a), (b) and (c). The average diameters of the coarse grains, medium grains and fine grains are, respectively, 477 microns, 162 microns and 23.6 microns.

Table I. Composition of Propellants

Number	NH_4ClO_4 Content in Weight Percent	NH_4ClO_4 Particulate Distribution (Weight Distribution)	Polyester Resin Content in Weight Percent	Powdered Carbon Content in Weight Percent
APE-7	80	Fine	20	0.13
APE-8	80	Medium	20	0.13
APE-9	80	Coarse	20	0.13
APE-1	75	Fine	25	0.13
APE-13	75	Fine	25	0
APE-4	75	$\frac{1}{2}$ Fine + $\frac{1}{2}$ Medium	25	0.13
APE-11	75	Medium	25	0.03
APE-3	75	Coarse	25	0.13

As an additive, propellants in general have 0.13 percent powdered carbon added, but in order to examine the effects of the powdered carbon, test specimens were made containing no powdered carbon at all. Moreover, no propellant included powdered aluminum.

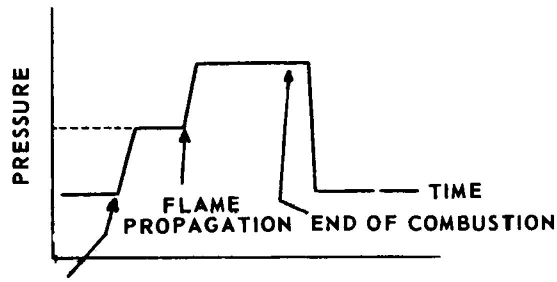

Figure 3. Change in Pressure within the Chamber with Passage of Time when the Flame Propagated into Cracks

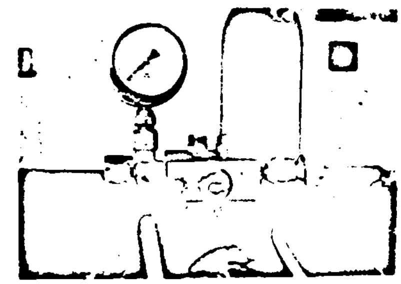

Figure 4. Pressure Chamber

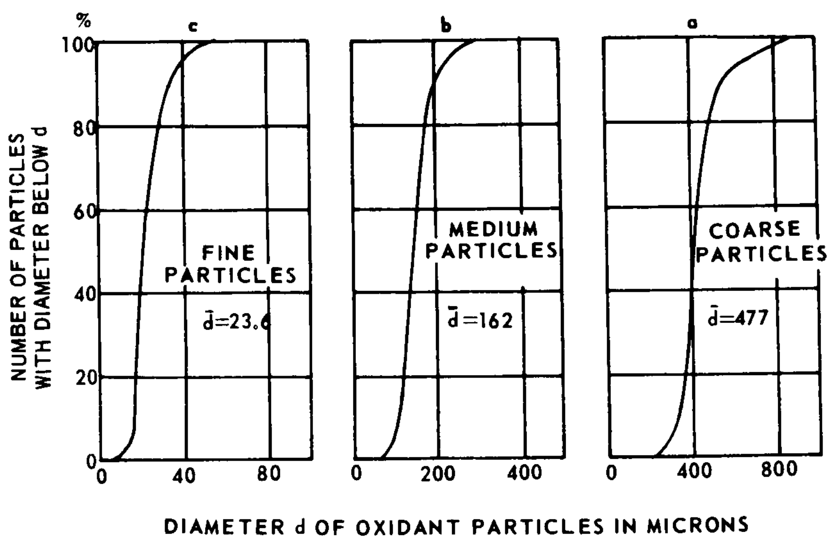

Figure 5. Particulate Distribution of Oxidant

3. EXPERIMENTAL RESULTS

The effects of the propellants' initial temperature on the threshold gap are shown in Figure 6. In the figure, "o" represents cases where the flame propagated into the cracks, while "•" represents cases where the flame did not propagate into the cracks. No matter whether the temperature was + 25°C, 0°C or -25°C, the flame propagated into the cracks if the crack gap was 0. 25 mm or greater. However, if the crack gap was 0. 20 mm or less, the flame did not propagate into the cracks. In other words, we see that there is a threshold gap between 0.20 mm and 0.25 mm. While, in general, there is a certain amount of spread in the threshold gap, it is believed that this is due not only to non-uniformity of propellant composition but also to shape of the cracks, inaccuracies in size and conditions on the propellant surface. As shown in Figure 6, there is little effect of the propellant initial temperature on the threshold gap t^*, and there is a tendency for t^* to increase somewhat as the temperature becomes lower. On the other hand, the linear combustion velocity decreases as the temperature decreases.

The effects of pressure on flame propagation into cracks is shown in Figure 7(a). While it is difficult to show clearly in one curve the threshold gap as a function of pressure, due to variation in the observation points, it is clear that there is a tendency for the threshold gap to decrease as the pressure increases. That is to say, as the pressure increases, it facilitates the propagation of flame into narrow cracks. Figure 7(b) shows changes in linear combustion velocity caused by pressure.

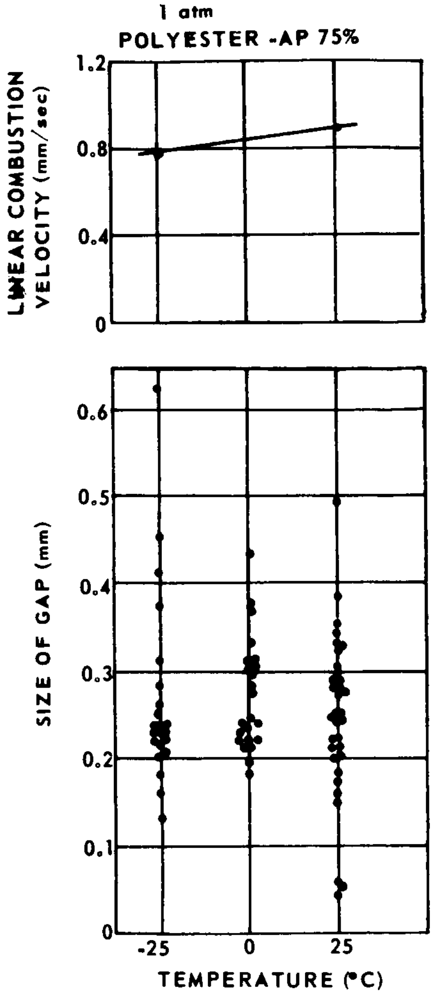

Figure 6. Effects of Propellant Initial Temperature on Flame Propagation into Cracks

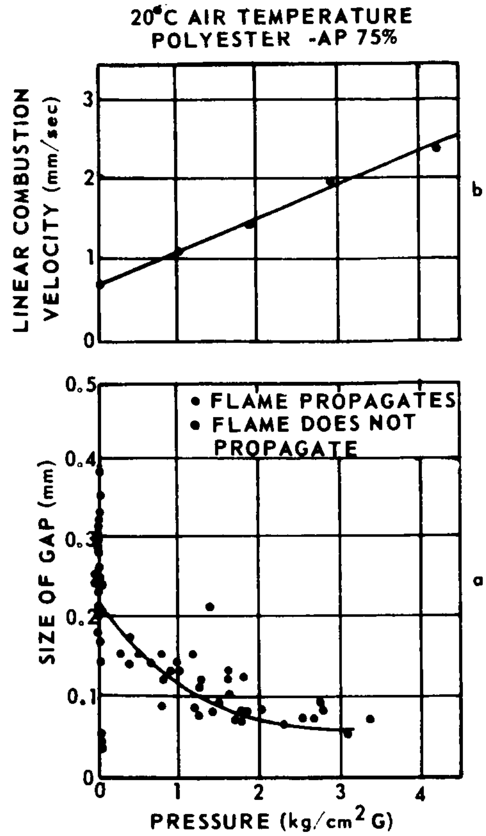

Figure 7. Effects of Pressure on Flame Propagation into Cracks

The effects of propellant composition on the threshold gap are shown in Figures 8 and 9. Figure 8 shows the effects of powdered carbon as an additive on threshold gap. Using as the base material a composition containing 75 percent fine particle ammonium perchlorate, it shows that there is no change in threshold gap for white propellant containing no powdered carbon whatsoever and a blackish propellant containing 0.13 percent powdered carbon.

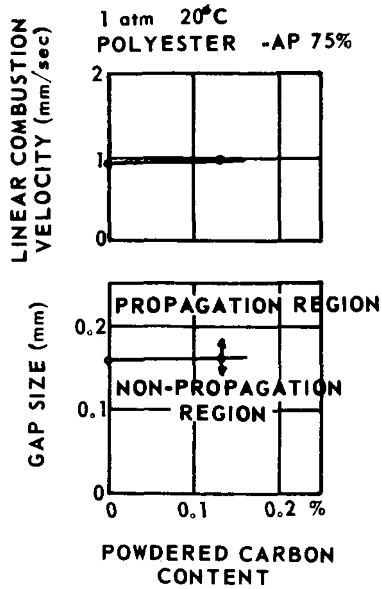

Figure 8. Effects of Added Powdered Carbon on Flame Propagation into Cracks

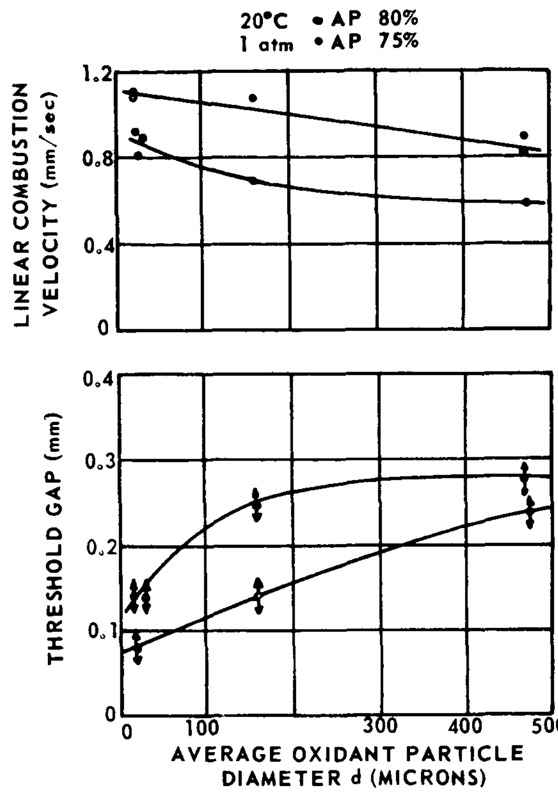

Figure 9. Effects on Flame Propagation into Cracks of Oxidant's Particulate Distribution and Content

Figure 9 shows the effects of ammonium perchlorate's particulate distribution and its content in percent vis-a-vis threshold gap. The threshold gap is smaller for a propellant containing 75 percent ammonium perchlorate than for that containing 80 percent. This tendency is a constant one, having no relation to particulate distribution. With respect to effects of particulate distribution, as shown in Figure 9, in comparison to the case where the average particle diameter is 23 microns, a fine particle, the threshold gap increases for propellants containing larger particles. However, the tendency for increased threshold gap decreases for propellants containing particles beyond a certain size.

4. CONSIDERATIONS

The effects of a propellant's initial temperature, environmental pressure and composition on threshold gap were studied separately. By consolidating these and plotting the threshold gap vis-a-vis the linear combustion velocity, we obtain Figure 10. While there is considerable spread in measured values in the ranges of 25°C to -25°C for the initial temperature, zero to 3.5 kg/cm^2 G for environmental pressure, oxidant content of 75 and 80 percent and average oxidant particle size of 23 to 477 microns, they are basically shown as functions of linear combustion velocity. In other words, the greater the linear combustion velocity, the greater is the tendency for threshold gap to decrease. Nevertheless, if we were to compare, for instance, a propellant with 75 percent content of an oxidant with average particle diameter of 23 microns with a propellant with 80 percent content of an oxidant with average particle diameter of 477 microns, while they both have the same linear combustion velocity, the threshold gap of the latter is approximately double that of the former. Accordingly, while the threshold gap is primarily a function of the linear combustion velocity, it is not determined entirely by the linear combustion velocity.

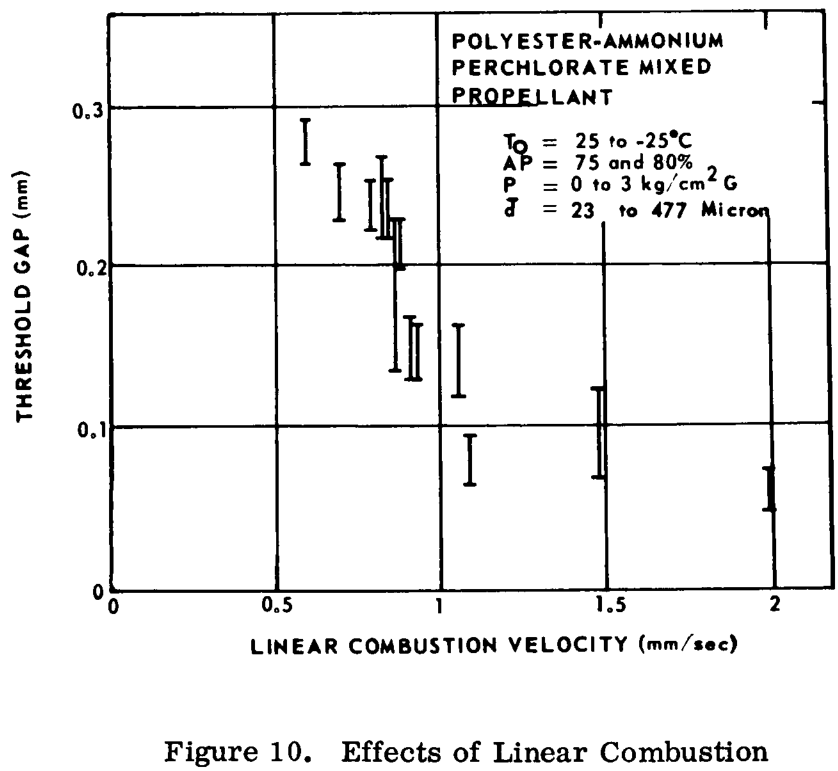

Figure 10. Effects of Linear Combustion Velocity on Flame Propagation into Cracks

When we qualitatively examine the phenomenon of flame propagation into cracks of solid propellants, we see that this phenomenon is similar to the quenching phenomenon in combustion of gases. When we compare these two phenomena, we find that the major difference is that in quenching, the wall around the gas flow is formed by incombustibles, while the wall is formed in this particular phenomenon by combustible solid propellant. While the combustion of solid propellant is governed mainly by mixing due to dissipation of oxidant vapors and fuel vapors as well as the chemical reaction accompanying this, it is believed that the speed of this will increase proportionately with propellants having high linear combustion velocity.

Assuming that the flame entered into the cracks, if the flame is cooled by the surrounding cool walls of solid propellant–that is to say, if the negative flame growth effect is greater than the positive flame growth effect due to mixing and chemical reaction–the flame which entered into the cracks will be extinguished. Accordingly, from the standpoint of phenomena, the flame will not propagate into the cracks. In the opposite case, where the cooling speed is less than the mixing and reaction speed, the flame will not be extinguished within the cracks. Accordingly, the flame will propagate into the cracks. Since the positive flame growth effect will be greater as the propellant's linear combustion velocity is greater, the flame will propagate into even smaller cracks. Fundamentally, it is believed that by considering such a model it is possible to explain this phenomenon.

5. CONCLUSIONS

With respect to flame propagation into cracks of solid propellants, we confirmed the following, using test specimens of composite polyester propellants:

1. There always is a "threshold gap" where the flame will propagate into the cracks if the gap of the cracks is greater, and where the flame will not propagate into the cracks if the gap of the cracks is less than this value.

2. The threshold gap is represented fundamentally as a function of the linear combustion velocity, although it is a function of the propellant's initial temperature, environmental pressure and composition. The threshold gap decreases as the linear combustion velocity increases.

In closing, I wish to express my gratitude to Technical Official Tamura of the Model Laboratory, who cooperated throughout the course of this study with me.

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